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An Analysis of Conditional Site Diversity: A Study at Ka-Band

Duncan David Hodges and Robert John Watson, *Member, IEEE*

Abstract—The use of EHF and SHF frequencies above 20 GHz is becoming increasingly important for high-capacity communication systems. Whether these systems are slant-path links, terrestrial fixed links, or deep-space links, the high bandwidths available and the relatively low spectral congestion are very attractive. One of the main disadvantages of these frequency bands is that the attenuation caused by meteorological effects can become significant, and the attenuation caused by clouds, rain, and atmospheric gases becomes very large. The largest attenuation events are caused by rain and clouds with a high liquid water content. In order to provide high-availability links, it is possible to use site diversity, by providing two spatially independent terminals. The spatial separation of the terminals reduces the probability of both terminals being faded. In this paper, we present an analysis of two spatially unique measurements of a satellite-based 20.7-GHz beacon. The results show that even at modest separations there is still the opportunity for significant availability improvements using site diversity. The probability density functions (pdfs) conditioned on the single-site attenuation level are presented. These demonstrate a characteristic shape and could form the basis of future modeling approaches.

Index Terms—Diversity methods, microwave communication, satellite communication.

I. INTRODUCTION

As the spectrum in the K- and Ku-band begins to reach saturation, the relatively free spectrum at Ka-, V-, Q-, and W-band is becoming more attractive [1]. Other advantages of this frequency space are the relatively large capacities that are possible. One disadvantage of this allocation is the effect from meteorological phenomena in the troposphere [2]. Rain, clouds, and atmospheric gases (notably oxygen and water vapor) cause significant levels of attenuation. The effects of scintillation are also increased at higher frequencies. Scintillation is caused by small turbulent irregularities in temperature, humidity, and pressure, which in turn cause small variations in refractive index. These small irregularities cause a fast-fading noise-like component on measured time series.

The International Telecommunication Union, Radiocommunications sector (ITU-R) predicted cumulative distribution [3] of the attenuation levels on a slant-path to a geostationary payload at 2° W is shown in Fig. 1. At frequencies above 20 GHz, the fades caused by atmospheric phenomena can be very large, and many operators will find that simply using a static fade

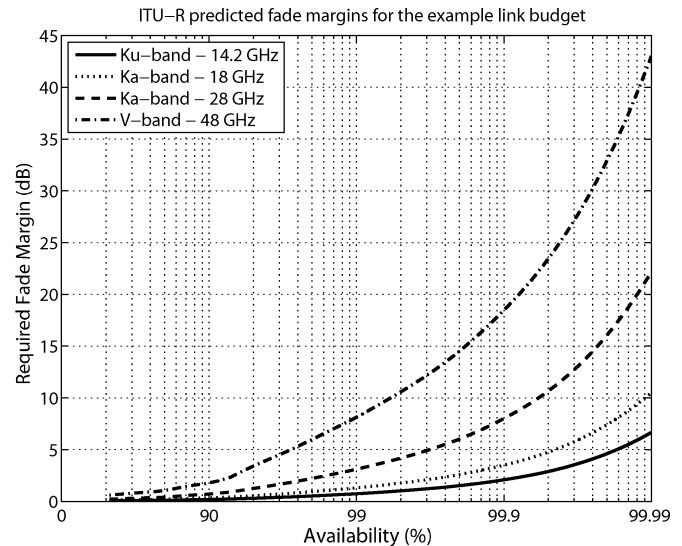


Fig. 1. CDF of the predicted fade level on slant-path from Bath, U.K., to a geostationary payload at 2° W.

margin will result in massively inefficient systems (with reference to the example shown in Fig. 1, it can be seen that at 40 GHz a fade margin of nearly 45 dB is required to provide 99.99% availability).

There are three different approaches to combating these fades and maintaining a highly available and high-efficiency systems [1], [4]–[6].

- **Power-control techniques:** These techniques represent a simple approach to mitigating fading. As the fade occurs, the power flux on the link is simply increased. This is either achieved by increasing the transmit power or through adaptive-antenna techniques.
- **Adaptive-waveform techniques:** These techniques vary the waveform that is used to ensure that a higher throughput is used in clear-sky conditions. Under fading, the waveform can be reduced to a lower throughput configuration to provide a more robust system. Techniques in this category include adaptive code rate and modulation (ACM) and adaptive data rate.
- **Diversity and resource management:** These techniques use a mixture of approaches to avoid transmitting data through large fades. These techniques include space and time diversity as well as other resource management approaches.

At lower frequencies power-control and adaptive-waveform techniques may prove to be sufficient to achieve high enough availabilities, however, ultimately their ability to combat very

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TABLE I
BRIEF REVIEW OF THE DAILY METEOROLOGY DURING 2004

Period	Max. Temp		Min. Temp		Mean Temp.		Sunshine		Rainfall	
	Actual (°C)	Anom. (°C)	Actual (°C)	Anom. (°C)	Actual (°C)	Anom. (°C)	Actual (hours)	Anom. (%)	Actual (mm)	Anom. (%)
December 2003 - February 2004	8.4	1.4	2.5	1.2	5.4	1.3	190.6	111	221.7	105
March 2004 - May 2004	13.8	1.3	5.2	1.0	9.5	1.1	474.0	102	172.1	101
June 2004 - August 2004	21.6	1.2	12.1	1.2	16.8	1.2	622.5	105	188.9	116
September 2004 - November 2004	15.1	0.8	7.9	1.1	11.5	1.0	334.9	103	199.4	90
January 2004 - December 2004	14.8	1.1	6.9	1.1	10.8	1.1	1613.4	103	756.2	99

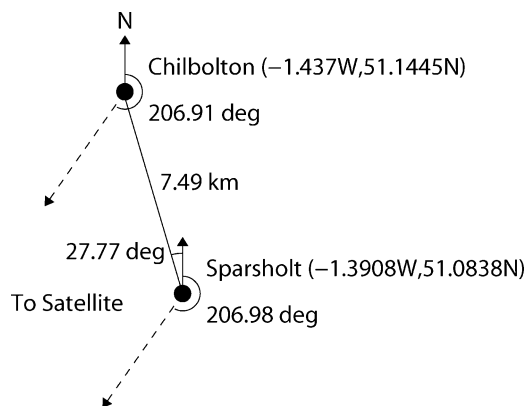


Fig. 2. Map of the measurement sites used in this experiment.

large fades is limited. Under these conditions, the only approach to mitigation is to avoid the fade entirely [7].

In these cases, site diversity may provide a means of reducing the apparent fade depth. Using a number of spatially separate terminals, it is possible to utilize whichever terminal is subjected to the least level of fading. The level of separation required is a function of the required improvement in availability and the climatology of the locations concerned. To aid with systems planning, this paper provides an insight to a site-diversity experiment performed at the two observatories run by the Rutherford Appleton Laboratory (RAL, Oxfordshire, U.K.).

II. SINGLE-SITE BEACON MEASUREMENTS

The measurements of the 20.7-GHz beacon, which is aboard the UFO-9 GBS satellite, were made at the two RAL observatories. These observatories are both located in southern England, one at Sparsholt (51.038° N, 1.3908° W) and Chilbolton (51.1445° N, 1.437° W) separated by about 7.5 km; these are shown in a topographic map in Fig. 2.

The beacon is located aboard a United States Department of Defence satellite in a geosynchronous orbit at approximately 23° W, which results in an elevation angle of approximately 30°. Although the satellite is in a geosynchronous orbit, it has a slightly inclined orbit (around 4°); the data are processed at RAL to remove the effects of this, however some evidence is still apparent. The beacon is left-hand circularly polarized and the attenuation relative to a clear sky is calculated, hence this analysis represents the attenuation caused by clouds and rain with no effect from the water vapor or oxygen absorption. The spatial variation of gaseous absorption is not significant and given

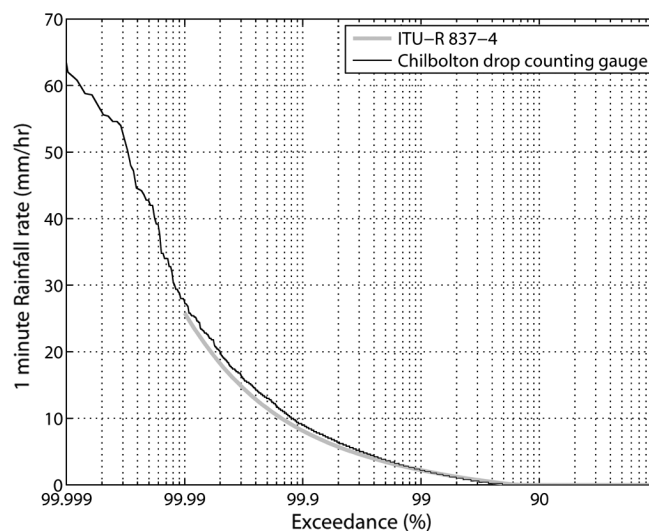


Fig. 3. CDF of 1-minute rainfall rate.

the level of gaseous fades at this frequency, the conclusions regarding site diversity will not be affected. An initial report and background to this measurement campaign can be found in [8].

The year 2004 has been chosen to perform the analysis, since this forms a large continuous data set of 1-s time resolution. The beacon availability during the length of this study was of the order of 99.995% for both beacon receivers. The United Kingdom Met-Office review of this year reports the average daily conditions for Southeast and Central England as shown in Table I along with the percentage anomaly (compared to the 1961–1990 average).

As can be seen, 2004 is slightly warmer and drier than the 1961–1990 average, however it can still be considered that 2004 represents a good proxy for the average yearly meteorology in the Southern United Kingdom.

A. Cumulative Distribution Functions

The annual cumulative distribution function (CDF) can be estimated from the ITU-R recommendation ITU-R P.618-8 [3] with the attenuation due to rain estimated using the rainfall rate distribution provided by ITU-R P.837-4 [9]. A drop-counting rain-gauge located at Chilbolton can be used to estimate the 1-min rainfall rate and this is compared to the distribution from the ITU-R recommendation. This comparison is shown in Fig. 3. The rainfall rate distribution from ITU-R P.837-4 slightly underestimates the rainfall rate distribution for 2004.

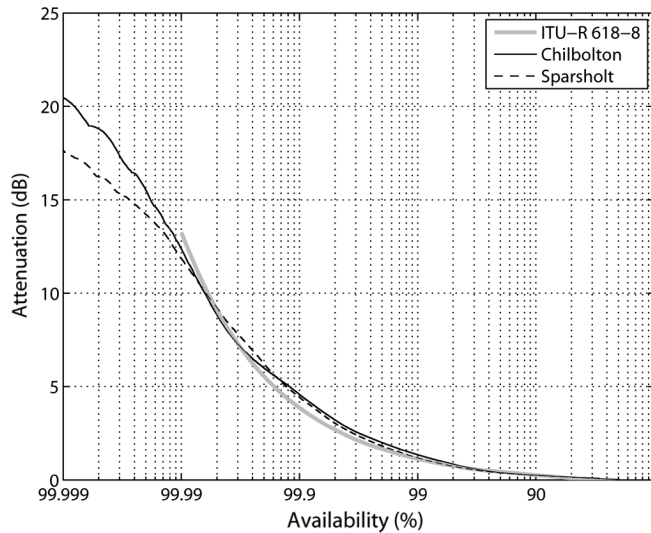


Fig. 4. CDF of the 20.7-GHz beacon measurements.

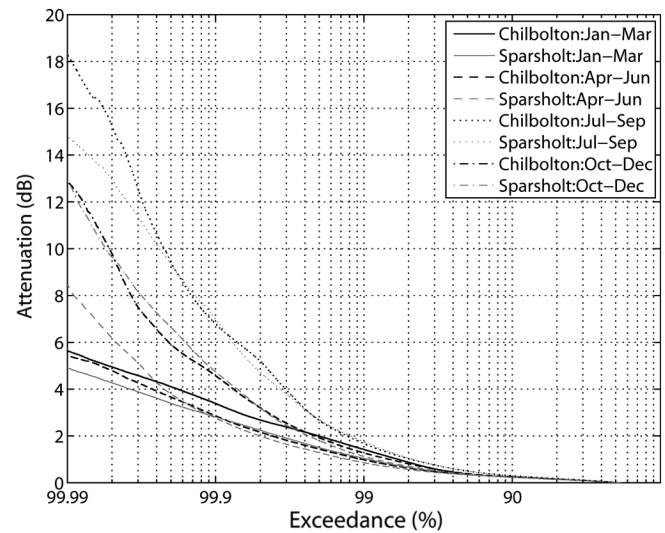


Fig. 6. CDF from four seasons for both receiver locations.

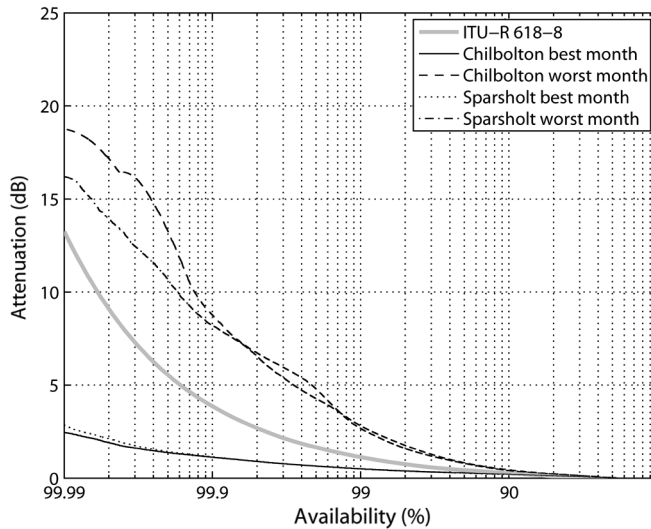


Fig. 5. CDF of the best and worst months for both receiver locations.

The annual CDFs of the beacon measurements from the two sites are included in Fig. 4 along with the ITU-R predicted attenuation. Comparing the beacon measurements with the ITU-R recommendation, it can be seen that the recommendation provides a good estimate of the yearly attenuation from tropospheric phenomena. This is in rough agreement with that seen from the 18.7-GHz beacon measured as part of the Italsat campaign [10].

Also of interest are the best and worst months for both locations as these encapsulate some of the seasonal variability that is present in the data set. These were calculated using a 30-day sliding window. For every location, the CDF of attenuation was calculated and the worst and best locations of the window were noted. The CDFs corresponding to the best and worst window locations for both receivers are shown in Fig. 5. In addition, the seasonal variations over four three-month periods are shown in Fig. 6. As expected, the variation from best to worst months is large, even at fairly modest availabilities. For example, at an

availability of 99.99%, there is a variation from 2 to greater than 15 dB. This seasonal variations further demonstrates the problems with using a static fade margin at these frequencies. For example, a fade margin that would provide an availability of 99.99% in the best month would only provide a 99% availability in the worst month. The seasonal variation is also significant, with the July–September period demonstrating the largest fading; surprisingly, the January–March period demonstrated the lowest fading levels. Since this is only one year of data, it is difficult to draw too many conclusions as to the seasonal variation other than the variation is significant.

III. JOINT FADE PROBABILITY AND DIVERSITY GAIN

Since there are two receivers situated 7.5 km apart, it is possible to analyze the joint fading probability and the diversity gain provided by this separation. The probability matrix M is defined as

$$M(x, y) = P(A_s = x, A_c = y) \quad (1)$$

where A_s and A_c are the beacon measurements at Sparsholt and Chilbolton, respectively. The probability matrix of the attenuation at the two sites is shown in Fig. 7, with the attenuation placed quantized into 0.5-dB bins and with each contour representing an order of magnitude.

If there were no spatial diversity, all off-diagonal elements of the matrix would be zero. However, as can be seen, there is significant spread away from the leading diagonal. This spread demonstrates the lack of short-term correlation, and hence, the viability of site-diversity fade mitigation techniques (FMTs).

A more illuminating measure is the value of the diversity time series $D(t)$. For the two locations, this can be expressed as

$$D(t) = \min[A_c(t), A_s(t)]. \quad (2)$$

The CDF of this diversity time series is shown in Fig. 8 along with the individual location CDFs from the two sites.

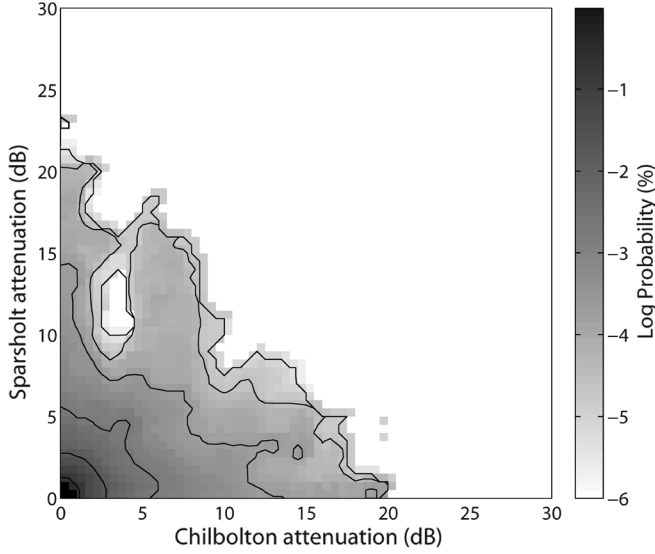


Fig. 7. Probability matrix of the slant-path attenuation at Sparsholt and Chilbolton.

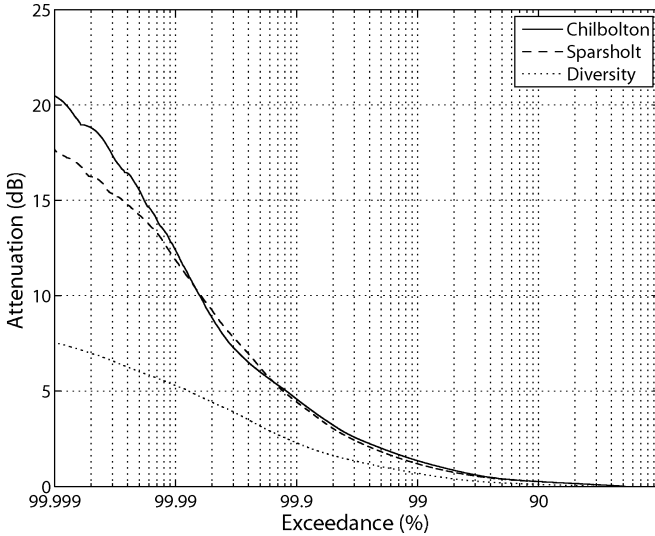


Fig. 8. CDF of the 20.7-GHz beacon measurements and the diversity time series.

As can be seen, statistically, there are large gains to be achieved using even this modest spatial separation. The CDF of the diversity time series follows a similar curve to the single-site time series until approximately 7 dB where the gradient of the diversity time series reduces. This is to be expected, since the fades at high availability $>99.9\%$ will be caused by severe rain-fall rates, which in turn will most likely be highly convective. The spatial correlation of such events is likely to be very small.

The ITU-R [3] defines a diversity gain G_D , which, in the case presented here, can be defined as

$$G_{DC}(t) = A_c(t) - D(t) \quad (3)$$

$$G_{DS}(t) = A_s(t) - D(t) \quad (4)$$

where G_{DC} and G_{DS} represent the diversity gain at Chilbolton and Sparsholt, respectively.

One approach at this point is to compare the equiprobable attenuation and site-diversity gain. The Allnut-Rogers model [11]

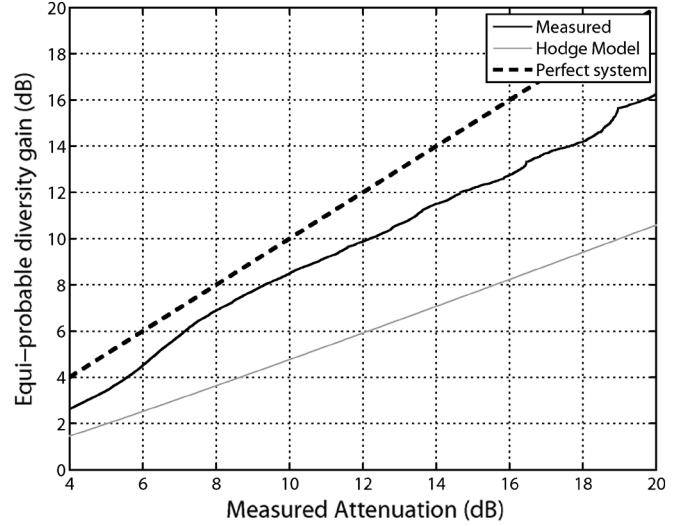


Fig. 9. Comparison between the Hodge model (ITU-R P.618-8) and the measured equiprobable diversity gain.

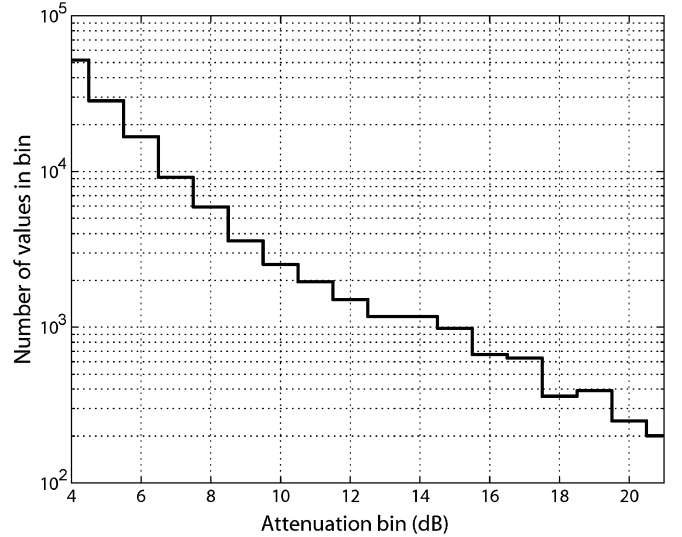


Fig. 10. Number of members of the set t_a for each attenuation level.

assumes that the separation between the receivers is larger than the average cell size; this showed poor results with receivers separated at 10 km but worked well for receivers separated at distances of 35 km. The core assumption of this model does not hold in this case. The model of Hodge [12] calculated the equiprobable diversity as an empirical fit to a number of characteristics such as link separation, frequency, etc.; a form of this model has been adopted by the ITU-R and forms the recommendation P.618-8 [3]. A comparison of the measured attenuation and the equiprobable site-diversity gain is shown in Fig. 9. As can be seen, the model dramatically underestimates the available gain; this has also been noted before [13].

In order to provide a better insight into the behavior of the site diversity, the probability distribution function of the diversity gain conditioned on the attenuation level $P(G_D|A)$ can be used. The conditional probability is defined as

$$P(G_D|A) = \frac{P(G_D \cap A)}{P(A)}. \quad (5)$$

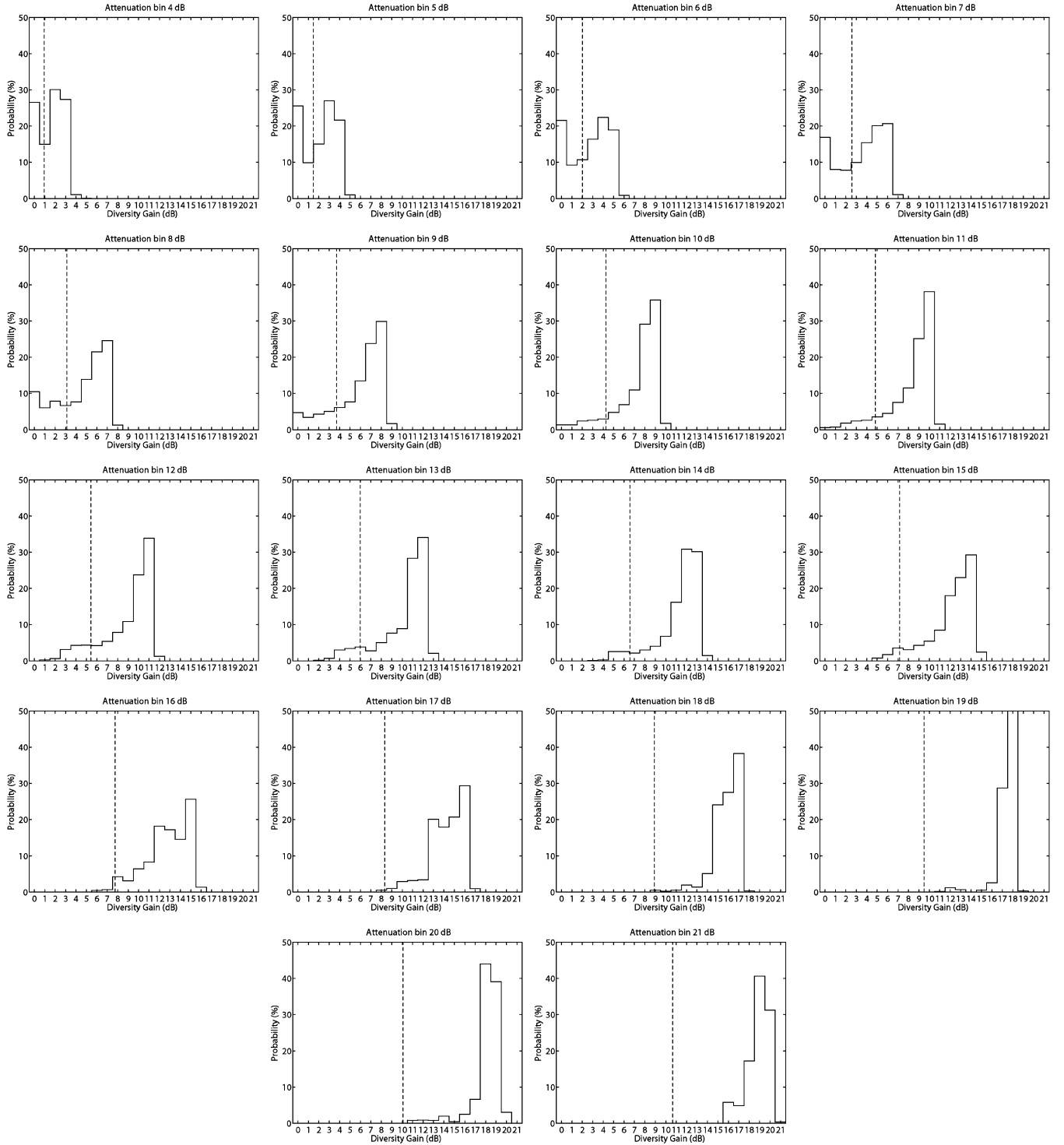


Fig. 11. Conditional pdfs of the diversity gain calculated using (3).

In this analysis, the set of times for which the attenuation fell within a given bin was calculated

$$\{t_a(A) : (A - \delta A) \leq A \leq (A + \delta A)\}. \quad (6)$$

The value of $P(G_D|A)$ is then calculated from the set of diversity gain at time t_a . The number of members of the set t_a for a given attenuation is shown in Fig. 10. As can be seen, there is a

statistically significant number of points up to the 21-dB attenuation bin. The conditional probability density functions (pdfs) from (3) are shown in Fig. 11. The ITU-R predicted diversity gain [3] is denoted by the dotted vertical line.

It can be seen that there are two distinct regimes to the conditional distributions. In the first regime, associated with smaller attenuation levels, up to 7 or 8 dB demonstrate a bimodal distribution. The first peak that decreases in magnitude as the attenu-

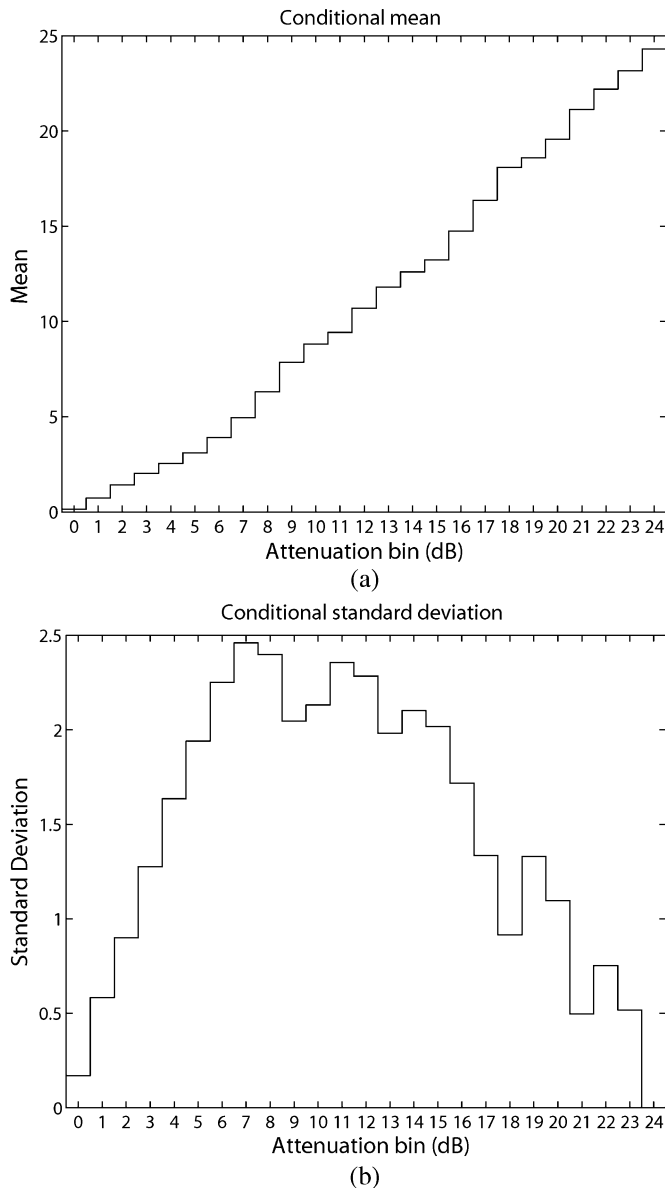


Fig. 12. Moments of the conditional pdfs of the diversity gain. (a) Mean. (b) Standard deviation.

ation bin increases represents a diversity gain of 0 dB; this is the case when the considered location is the location with the lowest attenuation or when both locations are equally faded (e.g., widespread frontal rain).

Evidently, as the attenuation level increases, the probability of the considered location having the lowest attenuation is reduced. Further, since high rainfall rates and high liquid-water clouds tend to be spatially smaller in extent, the probability of both locations being equally faded is also reduced.

The second regime demonstrated by the conditional distributions occurs at higher frequencies and demonstrates a situation where the mode of the distribution is very high and is approximately the same as the attenuation level. The distribution is heavily skewed with the mean at the upper-end of the distribution. The standard deviation decreases and while the kurtosis increases, this is clearly seen in the first four moments of the conditional distribution, shown in Fig. 12.

It can be seen that the peak in the standard deviation clearly denotes the change in the diversity gain regime, which in itself is closely linked to the climatology and separation of the considered locations.

Also well demonstrated is the deficiency of the ITU-R recommendation; at relatively low attenuations, the ITU-R recommendation can be seen to be representative of the conditional mean of the diversity gain; however, when the standard deviation starts to decrease and the distribution changes from the bimodal distribution, the recommendation becomes unrepresentative. This has also been seen in rainfall rate data measured in Spain [13].

IV. CONCLUSION

In this paper, we have presented a thorough analysis of the global broadcast service satellite (GBS) beacon measurements made in the Southern United Kingdom by the RAL. The two receivers were situated at two locations separated by approximately 7.5 km.

The CDF of the attenuation at individual sites is well modeled by the ITU-R recommendation [3]. The variability from best to worst month is significant, of the order of 8 and 12 dB at 99.9% and 99.99% availability, respectively. This variability is a good indication of the efficiency advantages to be gained by fade mitigation techniques (even at this relatively low frequency).

The pdf of the diversity gain conditioned by the attenuation is the most useful measure of the viability of site diversity, since this describes the pdf of the diversity gain as the fade level is encountered. This measure demonstrates two distinct regimes. At low attenuation levels (in this case, at levels ≤ 7 dB), the pdf demonstrates a bimodal distribution and the ITU-R recommendation models well the mean of the distribution.

The second regime (in this case, ≥ 7 dB) demonstrates a unimodal distribution where the mode is very high (often near the attenuation bin considered). This second regime is poorly modeled by the ITU-R recommendation. This second regime is related to very high rainfall rates, which will most likely be convective events that typically have a much smaller spatial extent. This represents a significant shift in the underlying meteorological processes causing the attenuation, and hence, we should not be surprised at this regime shift.

The moments of the conditional distribution can be used to illustrate the attenuation at which the regime shift changes; with reference to Fig. 12, the shift can be seen as a change in the gradient of the mean of the conditional pdfs. The shift is even more evident in the standard deviation of the conditional pdfs. The standard deviation can be seen to increase linearly with the attenuation bin until the change point at which case it begins to decrease.

Before a thorough model can be created, more data are required covering different separations and different climatologies as well as different link characteristics. The approach of modeling the diversity gain pdf conditioned upon the single-site attenuation level can be seen to provide a good (and appropriate measure) for system designers particularly at higher Ka-band in addition to W-, V-, and Q-band where the attenuation caused by meteorological effects is so large that nondiversity FMTs will not provide significant availabilities.

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